R. A. Jaisinghani
Manager, Filtration Research,
Corporate Research Dept.,
Nelson Industries, Inc.,
Stoughton, WI 53589

G. S. Sprenger
Research Engineer,
Corporate Research Dept.,
Nelson Industries, Inc.,
Stoughton, WI 53589

A Study of Oil/Water Separation in Corrugated Plate Separators

Simplified trajectory calculations and small scale experiments suggest that the mechanisms of oil separation in corrugated plates are similar to those of other plate separators and that the radius of curvature is not an important design parameter. Bouyancy force and flow fields control oil drop rise, while drop-interface coalescence should be important when plates are completely oil covered. Results suggest that interdrop coalescence, due to the periodically constricted and expanding flow, is not an important mechanism.

Large scale (3–6 gpm) tests show that with light influent oil, corrugated plate separators perform better than simpler baffled vessels. With viscous, low interfacial tension oils, a simpler baffled separator performs better than the corrugated stack separator. This is probably due to viscous oil blockage in the plates and formation of a "foamy" oil-water mixture of high specific gravity.

Introduction

Due to overwhelming evidence of environmental and health hazards caused by increasing amounts of oil discharged in natural waters, there has been considerable governmental regulatory and standards activity related to oil pollution. Existing regulations governing industrial and marine vessel discharge have been recently analyzed by the University of Mississippi Law Center [1]. One of the consequences of this activity has been a growing interest in the research, development and evaluation of oily water separation processes and equipment. The special constraints such as size, simplicity of operation and variable fluid and operating conditions warrant special emphasis on the study of bilge and ballast oily water separation.

Typically, current shipboard and other oily water separation equipment include a primary gravity separation device [2, 3, 4, 5]. Gravity settlers may be classified as batch holding tanks, continuous flow baffled units and parallel or corrugated plate separators. One of the advantages of corrugated plates over parallel plates is that corrugated plates provide greater oil collection spaces and surface area. The flow direction in corrugated plates is generally as shown in Fig. 1(*a*), although the plates may be inclined. Oil drainage (from plates) provisions vary from configuration to configuration. There are numerous corrugated plate configurations used in gravity settling devices. U.S. patents dating as early as 1888 [6] and 1929 [7] describe enhanced oil water separation via use of corrugated plates.

Plate separators are generally accepted as providing enhanced oil separation over simpler baffled gravity settlers occupying the same space [2]. However, according to a technology review by Osamor and Ahlert [2], the main problem with plate separators is that they are susceptible to plugging by solids, biological growth or highly viscous oils. In general there has been little published data [8, 9] on the performance of these devices under various fluid conditions especially with highly viscous oils.

A field study of bilge samples from inland tow boats was conducted at Nelson Industries. Results of this study, relevant to this paper, are reported in Table 1. The range in variation of oil viscosities and other properties in bilge samples is evidently wide. The high viscosities are probably due to the nature of the oil and due to the effect of the suspended solids in the oil [10]. Similarly an emulsion of water-in-oil may also contribute to the high viscosity of the "oil". The low interfacial tension and surface tension of water indicate the presence of significant amount of surfactants.

The scope of this paper is to study oil/water separation in a corrugated plate separator configuration. Special attention was paid to the separation of highly viscous oils, such as reported in Table 1.

Effect of Plate Configuration

Design methods of horizontal gravity settlers have been reported by Abernathy [11]. Design equations and construction details of horizontal flow vessels are given by API [12]. In this section the effects of corrugated plate configuration on oily water separation will be considered.

Enhanced oil/water separation in corrugated plates may be due to:

a. Increased surface area and reduction in settling distance.
b. Drop-interface coalescence on plates coated with oil.
c. Coalescence due to the collision of droplets in periodic accelerated and decelerated flow in corrugations i.e. gradient coagulation.[1]

[1] Due to the periodic accelerated flow, drops of different sizes will have relative motion with respect to one another. Thus, small drops can vortex around larger ones and coalescence may occur if the film in between the drops is drained and ruptured before the drops separate in the flow field. Obviously, this mechanism will be more important for drops in air than in liquids.

Contributed by the Crew Systems Committee and presented at the Environmental Systems Conference, San Francisco, Ca., July 16–19, 1979 of THE AMERICAN SOCIETY OF MECHANICAL ENGINEERS. Manuscript received at ASME headquarters April 10, 1979. Paper no. 79-ENAS-26.

Table 1 Some Characteristics of Inland Vessel Bilge Samples

Parameter	
A. Oil Phase	
Specific gravity, gm/cc	0.88-1.01
Viscosity, cp	2.4-2000
Suspended solids, mg/l	
>105 microns	304-1104
> 1 micron	500-1600
Surface tension, dynes/cm	28-33
B. Water Phase	
Suspended solids, mg/l	
>105 microns	27-120
>0.2 microns	80-1410
Surface tension, dynes/cm	34-60
pH	4.5-8.5
Conductivity, micro MHOs/cm	79-2500
C. Interfacial Properties	
Interfacial tension, dynes/cm	<2
Zeta potential, mV	(+2)-(-40)

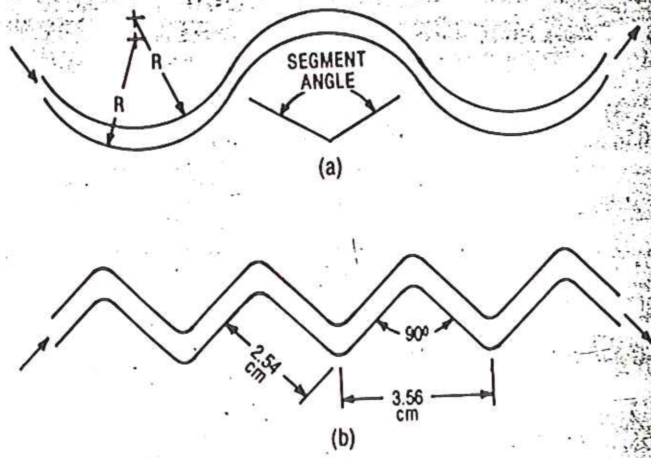

Fig. 1 Corrugated plates (*a*) Typical rounded plates (*b*) Right angled plates

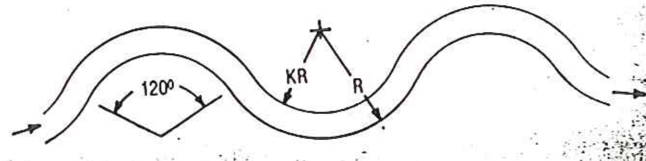

Fig. 2 Flow channel assumed for drop trajectory calculations

The first two mechanisms do not distinguish the corrugated configuration from plate separators. Osamor and Ahlert [2] consistently refer to such devices as gravity separators. Flow and buoyancy forces will control drop approach to the top plates, while coalescence will dominate the attachment of such a drop, when there is a spread film of oil on the plates. Sherony and Kintner [13], in their study of coalescence in fibrous beds, conclude that gradient coagulation or coalescence is unimportant since they were unable to observe this mechanism. The applicability of the above statement may be questioned since the drop sizes of importance here, are greater by an order of magnitude. If gradient coagulation is an important mechanism, then the radius of curvature (Fig. 1(*a*)) should be an important design parameter; for stacked corrugated plates, at a given mean separation and segment angle (Fig. 1(*a*)), the radius of curvature will control the number and gradient of the constrictions and expansions. Note that it is not possible to stack identical corrugated plates without having periodic constrictions and expansions. The importance of these effects have been studied by simplified drop trajectory calculations and small scale experimental work.

Simplified Drop Trajectory Calculations. The procedure is briefly described. For mathematical simplicity, a corrugated channel of consistent separation distance is taken to simulate corrugated plates (Fig. 2). Note that such a configuration is not practical since such plates cannot be stacked. However, if gradient coagulation is not important this is a fair approximation of realistic corrugated plates. Each section of the corrugation, then, is a segment of two concentric cylinders of radius R, and KR (Fig. 2). Obviously, it is difficult to accurately determine the flow field in this channel for a wide range of flow velocities. However, for the low flow velocities and small plate separations commonly encountered in corrugated plate devices, certain assumptions which simplify the analysis, may be justified. This simplified analysis does provide some insight regarding the effect of corrugated plate configuration on oil drop capture when gradient coagulation can be ignored. A more rigorous approach is beyond the scope of this paper.

Fully developed laminar flow is assumed. Further, as the fluid moves from one "hump" to the other, the origin shifts (Fig. 2) and the velocity profile is assumed to remain fully developed. These assumptions are justified at low Reynold's numbers. For laminar flow between flat plates the entry length (to fully develop the velocity profile) is given by [14]:

$$L = 0.04 \times s \times \mathrm{Re} \qquad (1)$$

where Re is the Reynold's number based on plate separation, s. Most of the calculations were done at 40 cm/min average velocity and at 0.635 cm plate separation (i.e. Re = 42.3). Using the above equation for flat plates, the entry length for the above conditions is about 1 cm. In other words, for these curved channels the flow field develops rapidly, if secondary flow can be ignored.

For flow in a curved channel contained within concentric cylinders, secondary flow is important for Dean numbers ($\mathrm{Re}(S/R^{1/2})$) exceeding a value of about 36 [15]. For most of these calculations (velocity = 40 cm/min and s = 0.635 cm) the Dean numbers are less than 30. Hence secondary flow is not considered in this analysis. Obviously, for the higher velocity calculations (Fig. 3) the validity of this assumption may be questioned.

The oil drops are assumed to behave as solids i.e., the effect on settling velocity due to internal drop circulation and drop distortion in a pressure field is ignored. This assumption should be valid for viscous oils. Also, the plates are considered to be wide so that side end effects are ignored.

The velocity profile (obtained from Navier Stokes equations with zero velocity at the walls) valid for these assumptions is:

$$V_\theta = \left\{ \frac{r \ln(r)}{2\mu} - \frac{r}{4\mu} + \right.$$

Nomenclature

C = Constant
g = Acceleration due to gravity
K = Ratio of inner to outer radius
L = Entry length
p = Pressure
Q = Flow rate
r = Radial coordinate
R = Outer radius; radius
s = Plate separation distance
S = Length of drop approach to the top plate
t = Time
V = Velocity
W = Width of plate
μ = Viscosity
ρ = Density of water
θ = Angular coordinate

Subscripts and Superscripts

p = Oil drop
r = Radial
θ = Angular

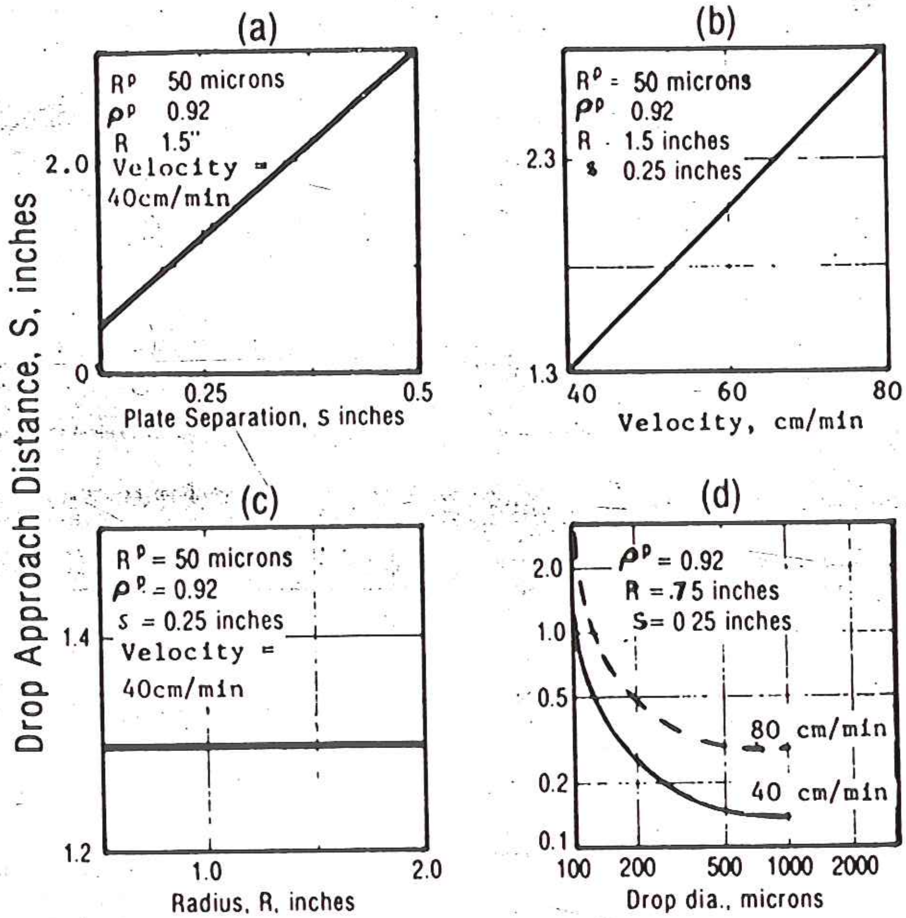

Fig. 3 Results of trajectory calculations

$$\left[\tfrac{1}{2} - \ln(R) - \left(\frac{K^2}{1-K^2}\right)\ln\left(\frac{1}{K}\right)\right]\left(\frac{r}{2\mu}\right) + \frac{K^2R^2}{2(1-K^2)r\mu}\ln\left(\frac{1}{K}\right)\Bigg\}\frac{dp}{d\theta} \qquad (2)$$

$$V_r = 0 \text{ (No secondary flow)}$$

The pressure gradient is found by a numerical iterative procedure such that the total volumetric flow rate is preserved. This technique has also been used by Pantankar et. al., [16]. A semi-empirical expression that approximates this gradient was found to be:

$$\frac{dp}{d\theta} \sim \frac{CQ(R+KR)}{W(R-KR)^3} \qquad (3)$$

where $C \sim 256$. Equation (3) provided the initial value for the iterative procedure.

The net force on an oil drop is then the sum of bouyancy force and drag (determined for laminar flow over spheres) forces. This then readily gives the trajectory equations:

$$\frac{dVp_r}{dt} + aVp_r = b \sin\theta \qquad (4)$$

and

$$\frac{dVp_\theta}{dt} + a\,(Vp_\theta - V_\theta) = b \cos\theta \qquad (5)$$

where

$$a = \frac{9\mu}{2(R^p)^2\rho^p} \qquad (6)$$

$$b = \frac{(\rho - \rho^p)g}{\rho} \qquad (7)$$

These equations were solved numerically using a finite difference approach. Initially, the drop was assumed to be at a distance of 0.06 cm away from the bottom plate, moving at the local fluid velocity at the entrance. Such a procedure then gave the drop trajectory. Since the drag terms in the force balance are inaccurate near the wall, the numerical calculation was stopped at a distance of 0.06 cm away from the top plate. The horizontal length travelled to achieve this condition (termed drop approach distance, S) was taken as an inverse measure of separation efficiency of the configuration. Obviously, the horizontal distance required to separate the oil drop determines the length of the vessel.

Results and Discussion. Qualitatively the analysis should point out the important factors affecting gravity settling in corrugated plates. Obviously this analysis ignores gradient coagulation and only considers horizontal approach distances, S, to the top plate. Some of the calculation results are shown in Fig. 3. As expected, the results show that:

a) $S \propto$ Plate Separation, s (Fig. 3(*a*))
b) $S \propto$ Velocity (Fig. 3(*b*))
c) $S \neq f(R)$ (Fig. 3(*c*))
d) S is a nonlinear, asymptotic, inverse function of drop size (Fig. 3(*d*)).

Results (*a*) and (*b*) are expected for plate separators. Result (*c*) and the drop trajectories show that the net effect of radius of curvature is negligible in the practical range of R = 1.27 to 3.81 cm.

Small Scale Experiments. Since the trajectory calculations do not take into account the periodic constrictions in corrugated plates, small scale experiments were conducted to evaluate this effect. Comparison of the results of these experiments with the simplified trajectory calculation results, will then provide some insight as to the importance of the radius of curvature and the gradient coagulation mechanism.

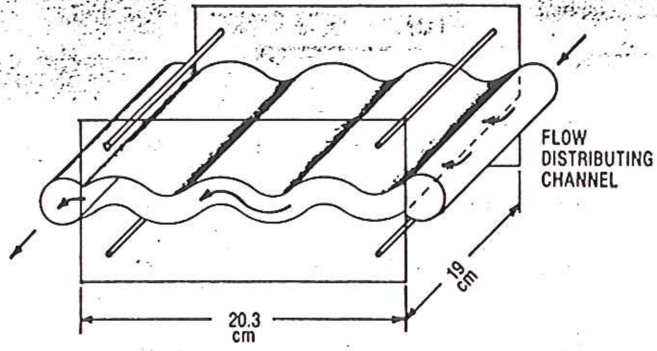

Fig. 4(*a*) Small scale corrugated plate assembly

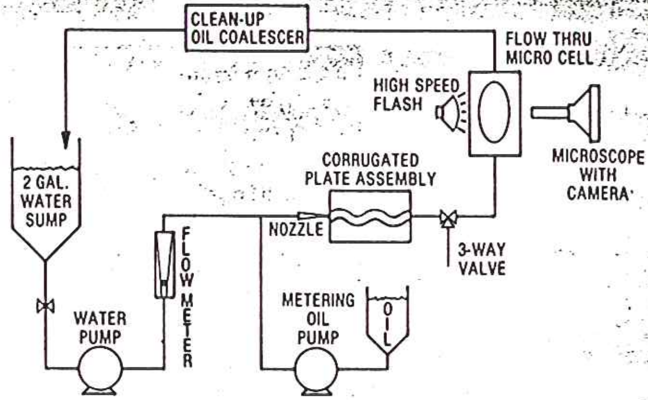

Fig. 4(*b*) Small scale experimental schematic flow chart

Small scale experimental work was conducted such that various plate configurations could be carefully evaluated. The apparatus used is shown in Fig. 4(*a*). It basically consists of a bolting assembly such that plexiglass sheets with variable gaskets could be used to seal the sides of the corrugated plates. The flow is well distributed at both the inlet and outlet. Fig. 4(*b*) shows the schematic flow chart. A fine nozzle (0.08 cm diameter) was used to create an influent drop size distribution at an average flow velocity of 33.0 cm/min. Mil 5606 hydraulic oil with specific gravity of 0.92 was used at 2000 ppm influent concentration. Plates used were made of aluminum and were covered with an oil layer before assembly so as to avoid transient effects during the process of establishing an oil layer; performance can be affected during this time period since adhesion characteristics between oil drop-plate material and oil drop-oil interface may be significantly different. In one case fiberglass reinforced plastic plates were used. The plates were carefully assembled such that the required average separation distance (average of all the maximas and minimas in separation distance) was achieved. The radius of curvature of the plates was varied from 0.635 cm to 3.0 cm and the segment angle (see Fig. 1(*a*)) was maintained at 90 deg for all cases, except for the fiberglass reinforced plastic corrugation (Table 2) and the right angled corrugation (Fig. 1(*b*)). Different radii of curvature resulted in different numbers and gradients for expansions and contractions. The overall dimensions of the plates were 19 cm wide by 20.32 cm long. Note that the flow velocity (33.0 cm/min) and plate separation (0.4762 cm) are within the range recommended by Mittleman [9].

After assembly, oil-water dispersion flow was started. The influent distribution was measured through an on-line flow-through cell using high speed photomicroscopy. The cumulative volumetric distribution is shown in Fig. 5. With the required depth of field it was not possible to use high magnification. This did not result in any significant error in the reported influent volumetric distribution (Fig. 9) due to the low volume fraction of the fine drops. In addition, effluent concentrations were measured by diverting the effluent into sample bottles (using the 3 way valve Fig. 4(*b*)). 100 ml samples were taken at 5, 10, 15, 30 and 45 minutes of elapsed time since dispersion flow was started. Effluent oil concentrations were measured using carbon tetrachloride extraction and IR analysis. Oil concentrations in the effluent were fairly consistent with time, and visually (by observing through the

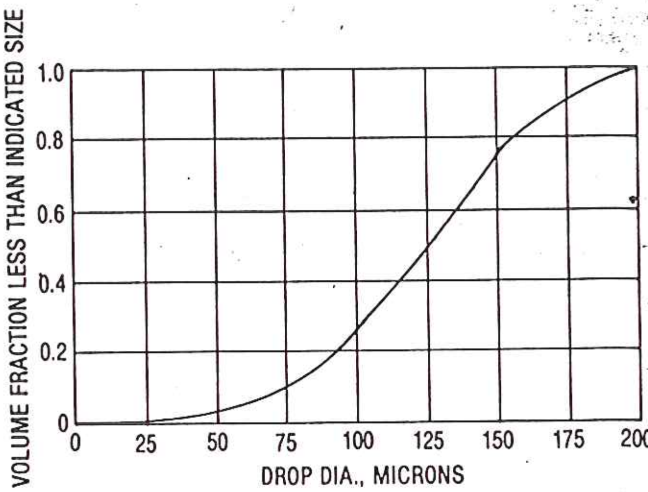

Fig. 5 Cumulative influent oil drop size distribution, small scale experiments

plexiglass sides) it was apparent that there was no significant oil build up in the plates with the 2000 ppm influent oil. Significant oil build up in the peaks of the corrugations could change the separation characteristics.

Initially, an attempt was made to photograph the drop distributions within the corrugations. This was aborted due to the inadequate magnification at the high required depth of field. For some of the runs, an attempt was made to measure the largest (average of largest five) effluent drops. This will be referred to as "cut-off" drop size. It was not possible to measure the entire effluent distribution due to the dual requirement of high magnification and high depth of field. Due to the low number of drops in the effluent, these attempts were not always successful in obtaining data of adequate confidence level and in general, the quality of the photographs were poor. However, it was possible to obtain *calculated* values of the "cut-off" drop size by using the known influent concentration, (2000 ppm), measured effluent concentration and the measured influence volumetric distribution

Table 2 Results of small scale experiments

Oil: Mil 5606 Hydraulic Oil
Inlet Oil Concentration: 2000 ppm
Flow Rate: 400 ml/min. (33.0 cm/min velocity)
Plate Length: 20.32 cm
Material of Construction: Aluminum
Sp. Gr.: 0.92
Plate Width: 19.0 cm
Temperature: 18°C
Mean Plate Separation: 0.4762 cm

No.	Corrugation Description: Shape	Corrugation Description: Radius cm	Corrugation Description: Segment angle, deg.	Corrugation Description: No. of Cycles in Corrugation	Measured Effluent Data: Range of Oil Conc. ppm	Measured Effluent Data: "Cut-Off" Dia. μm	Range of Calculated "Cut-Off" Dia. μm
1	Rounded	1.9	90	2.5	8-15	35	30-36
2	Rounded	1.27	90	3.25	6-11	*	28-33
3	Rounded	0.635	90	6.0	6-10	*	28-33
4	Rounded**	3.02	67	3.0	6-11	*	28-33
5	Rt. Angled	See Fig. 1(b)		5.75	14-41	*	36-49

* Inadequate photomicrographas or data not taken ** Fiberglass reinforced plastic

(Fig. 5). The calculated "cut-off" drop size is meaningful only if gradient coagulation is not important; obviously if this mechanism is important, then the values of calculated and measured "cut-off" drop sizes should not agree.

Results and discussion. Table 2 summarizes the results of the all scale experiments with the corrugated plates.

Upon examination of Table 2, it is clear the it would have been preferable to have conducted the experiments with a finer influent drop size distribution such that effluents of approximately 100 ppm were attained. Due to the low flow rates this was not conveniently accomplished by use of the nozzle. Feeding the oil into the suction side of the minicentrifugal pump (Fig. 4(*b*)) resulted in a fine dispersion such that the effluents were too high. However, under these conditions it is clear that the radius of curvature of the plates had little or no effect on plate performance (test nos. 1–4) in terms of both measured effluent oil concentration and calculated drop "cut-off" diameter. In test no. 1 acceptable photomicrographs were obtained and the measured value of "cut-off" diameter agreed well with the calculated value. The radius of curvature determines the gradient and the number of expansions and contractions in corrugated plates of equal segment angles. As discussed previously, this suggests that gradient coagulation is not an important mechanism of oil separation in corrugated plates.

In test no. 4 the corrugated plates had a segment angle (Fig. 1(*a*)) of 67 deg. as opposed to 90 deg. in other cases. However, this configuration performed comparably to the others. The right angled configuration (Fig. 1(*b*)) did not perform as well as the rounded configurations (test no. 5). This is probably due to the expected flow instabilities in such a configuration.

In general the results of these experiments with realistic corrugated plates are in qualitative agreement with the trajectory calculations done for plates without any constrictions and expansions. This suggests that under conditions of perfect oil drainage (oil accumulations not greater than a film) as simulated in these experiments, corrugated plates separate oil mainly by capture (and thus also coalescence at the top plate surface). It is possible that the radius of curvature may affect the performance under conditions such that low oil drainage rates cause significant accumulation; the radius of curvature should affect the oil holding capacity in the peak sections of the corrugations.

Large Scale Evaluation

Having studied the effect of plate configuration on oil separation, a large scale (~5 gpm) prototype was built so that its performance could be evaluated under oil conditions similar to the bilge samples of Table 1. The scope of this investigation is to determine the degree of enhanced oil separation (if any) in a gravity separator, with corrugated plates, over simpler gravity separation devices such as horizontal flow vessels, with or without baffled plates.

Experimental Details. A horizontal housing (30.48 cm diameter) was constructed with two chambers—a primary chamber for bulk oil removal and a longer secondary chamber (Fig. 6(a)). The secondary chamber was constructed such that either a set of baffles (Fig. 6(*b*)) or a stack of corrugated plates (Fig. 6(*c*)) could be inserted. It was possible to evaluate *three configurations* of equal over-all dimensions:

a) empty secondary chamber (Fig. 6(*a*))
b) baffled secondary chamber (Fig. 6(*b*))
c) secondary chamber with stack of corrugated plates (Fig. 6(*c*))

The corrugated plates used in most of these tests are shown in Fig. 6(*d*) and described in Table 2, test no. 4. All corrugated plates had weep slots (Fig. 6(*d*)) for oil drainage. Plate separation was 0.635 cm. The corrugated plates were assembled using vertical threaded rods and the plate spacing was maintained by using appropriate metal washers on the threaded rods. The material of construction was fiberglass reinforced plastic. In some tests the right angled metal corrugations (Fig. 1(*b*)), with an acrylic coating, were used.

Fig. 7 shows the test schematic flow chart. A progressing cavity pump (Moyno™ Model No. 1L3) with a variable speed drive was used as the oil-water mixing pump. An in-line static mixer, followed by a curved tube sampler at the center of the pipe, was installed on the effluent side of the separator housing. Care was taken to ensure that

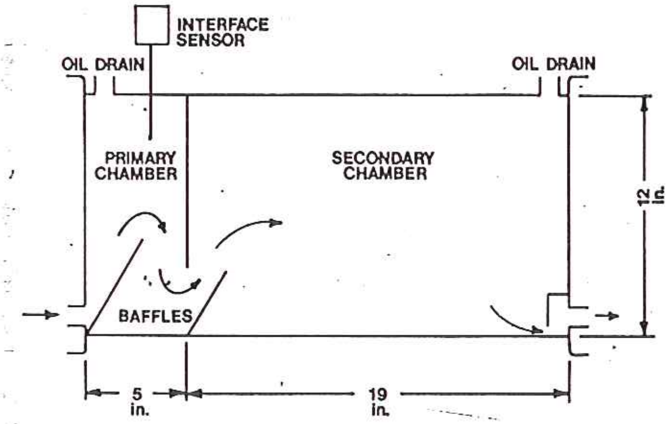

Fig. 6(*a*) Separator with empty secondary chamber

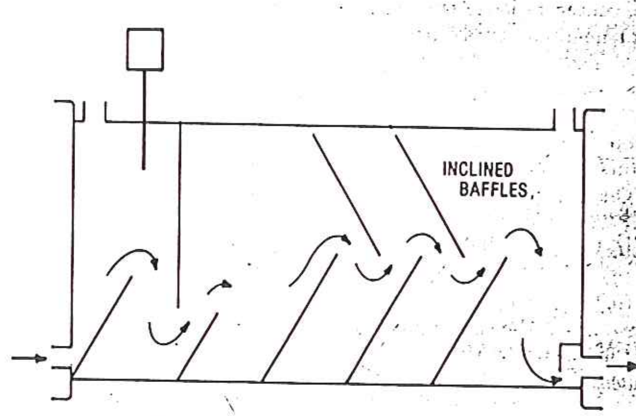

Fig. 6(*b*) Separator with baffled secondary chamber

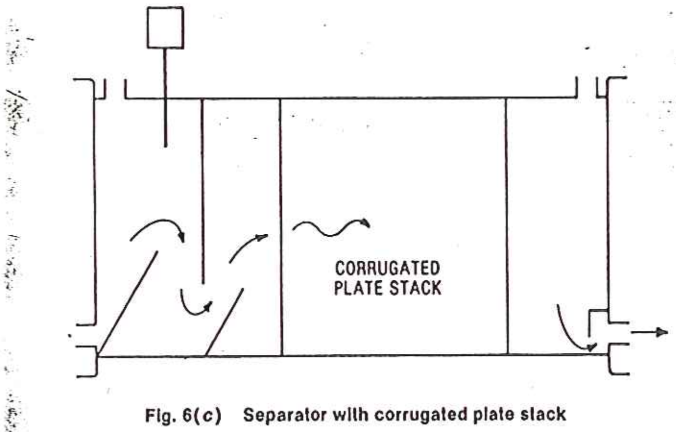

Fig. 6(*c*) Separator with corrugated plate stack

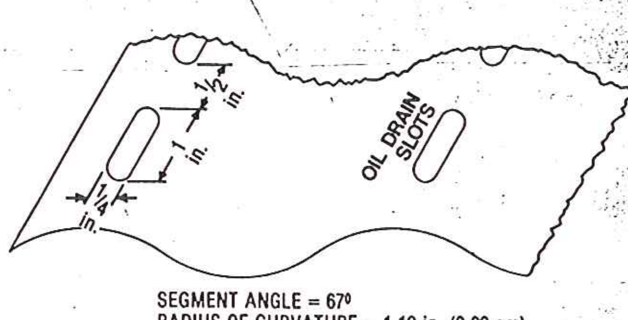

Fig. 6(*d*) Corrugated plate with weep slots

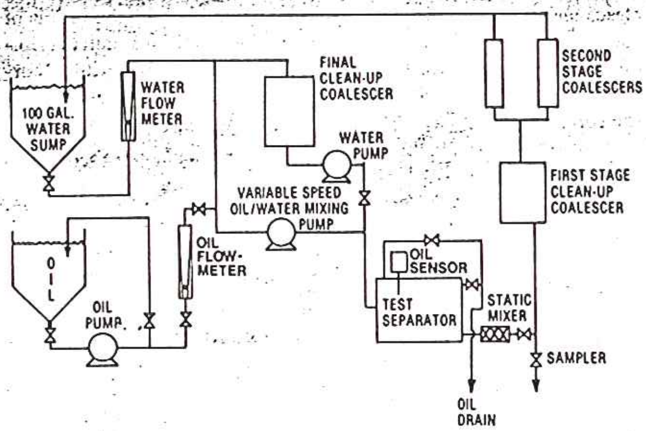

Fig. 7 Large scale test schematic flow chart

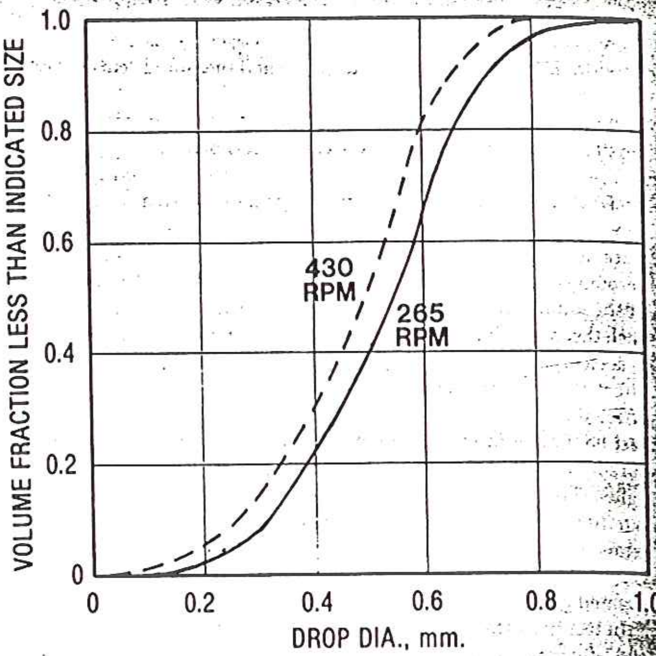

Fig. 8 Cumulative influent oil drop size distribution (50-50 mix, #2-#6 oils) for large scale tests

the oil concentration did not build-up in the secondary chamber. The oil concentration in the first chamber was controlled by a capacitance type oil-water interface sensor. Sampling during oil drainage was avoided. All the sampling was done isokinetically. About 500 ml of sample was taken and analyzed for oil content by carbon tetrachloride extraction followed by IR analysis. All tests were run for about 30–45 minutes and samples were withdrawn every 10 minutes. Preliminary work with this small scale separator had established that this time period was sufficient to overcome any significant transient effects.

Fairly low pump speeds (240, 340 and 430 rpm) were used to create the oil-water dispersion since such devices are not effective in removing fine drops [2]. The zeta potential is often a suitable measure of emulsion stability and upon examination of zeta potential values in Table 1, it is clear that the fine drops in bilge water can be stable enough such that they will not effectively coalesce on the plates of these devices. The accepted role of gravity settling devices is to remove bulk and coarsely distributed oil.

Drop size distributions, for an equal mixture of #2 fuel oil and #6 oil-in-water at 265 rpm and 430 rpm pump speeds, were measured by high speed photography of the flowing mixture in a plexiglass tube. Oil concentration of less than 1/2% was used for this measurement. At higher than 1/2% concentrations it was not possible to obtain reliable data due to oil accumulation on the sight tube. The distributions are plotted in Fig. 8. It should be noted that at significantly higher oil concentrations (i.e., approximately greater than 5%) the average drop size will be larger. With #2 fuel oil-in-water, the pump created a finer dispersion and with #6 oil the drop size was coarser.

Oils of three different viscosities and specific gravity were used at 65F–70F:

(*i*) #2 fuel oil (sp. gr. = 0.84, vis = 2.7 cp)

(*ii*) 50–50 mix of #2 and #6 oil (sp. gr.: 0.92, vis = 70–80 cp)

(*iii*) #6 oil (sp. gr. 0.96, vis = ~2000 cp) #6 oil was clearly non-Newtonian. Also note that it was difficult to maintain the consistency of the 50–50 mix. Most of the work was conducted at 5% influent oil concentration, and total flow rates of 4, 5 and 6 gpm.

Results and Discussion. Table 3 shows the performance of the three configurations with #2 fuel oil. Clearly, the corrugated plate stack performs significantly better than the baffled and empty secondary chamber configuration.

Table 4 summarizes the performance of the three configurations with #6 oil-in-water dispersion. Examination of the data in Table 4 leads to the following observations:

(1) The empty secondary chamber and baffled configurations perform better with #6 oil-in-water dispersions than with #2 fuel oil, mainly due to the larger drop size with #6 oil.

(2) The baffled configuration results in enhanced oil separation over the empty secondary chamber.

(3) The corrugated stack configuration performance is drastically retarded with this viscous oil. During this project, a smaller scale (1 gpm) plexiglass housing with corrugated plates was built to visually examine the movement of the oil. It was observed that the oil tenaciously clung to the plates and formed a dual emulsion or a "foam" consisting of pockets of water. (It was confirmed that there was no air leakage into the system). This "foam" was observed to bridge across large gaps between the end of the plates and the vessel internals. Further, the "foam" density approached that of water and eventually some of it found its way into the effluent.

The above visual observation may be useful in explaining the poor performance of the corrugated stack. The collected viscous oil does not drain through the weep holes due to its high viscosity and adhesion

Table 3 Large scale tests with #2 fuel oil

Oil: #2 fuel oil — Influent concentration: 5%
Temperature: 65F-70F — Viscosity: 2.7 cp — Sp.gr.: 0.84

No.	Secondary Chamber Configuration	Range of Effluent Oil Concentration, ppm @ 4 gpm	5 gpm	6 gpm	Mixing Pump Speed, rpm
1	Empty (Fig. 6(a))	115-130	125-135	190-220	240
2	Empty	-	380-450	450-600	340
3	Empty	-	1000-1100	1000-1300	430
4	With baffles (Fig. 6(b))	-	100-110	80-160	240
5	With baffles	-	150-210	280-310	340
6	With baffles	-	350-380	500-550	430
7	With corrugations*(Fig. 6(c))	-	10-25	10-35	240
8	With corrugations*	-	25-30	35-40	340

*0.635 cm plate separation; fiberglass reinforced plastic corrugations described in Fig. 6(d); plate length = 20.32 cm.

Table 4 Large scale tests with #6 oil

Oil: #6
Temperature: 65F-70F

Influent Concentration: 5%
Viscosity: 2000 cp
Sp.gr.: 0.96

No.	Secondary Chamber Configuration	Range of Effluent Oil Concentration, ppm @ 3 gpm	4 gpm	5 gpm	6gpm	Mixing Pump Speed, rpm
1	Empty (Fig. 6(a))	-	80-90	85-100	90-115	240
2	Empty	-	250-300	340-360	450-480	340
3	With baffles (Fig. 6(a))	-	50-65	60-75	110-120	240
4	With baffles	-	150-160	170-210	170-200	340
5	With baffles	-	350-1000	680-760	-	430
6	With corrugations*Fig. 6(c)	150-170	320-580	-	-	240
7	With corrugations*	-	1000-1140	1400-1600	-	430
8	With rt. angled corrugations (Fig. 1(b)) Plate length=25.4 cm	-	175-190	780-1460	-	240
9	Same as in (8)	-	1140-1830	910-3200	-	340
10	Same corrugations as above, except plate length=12.7 cm 1.27 cm separation	-	50-80	100-120	100-130	240

*0.635 cm plate separation; plate length 20.32 cm, fiberglass reinforced plastic corrugations as described in Fig. 6(d).

to the plates. This restricts the flow and causes flow instabilities which result in "foaming" due to the low interfacial tension and resilient interfacial films usually found in residual oil-water interfaces. This "foam" obviously will not readily settle. Also, the viscosity of the "foam" (or water-in-#6 oil emulsion) should be much higher than the #6 oil itself [10]. This can further increase oil blockage in the plates, increase average flow velocity and deteriorate oil capture. Some of the oil that does not form a "foam", will not readily flow through the weep holes, due to the high viscosity, and will be released at the same elevation as it entered the plate. All the plates had drain slots of 0.635 cm (0.25 in.), width × 2.54 cm (1 in.) length with center-center distance of 3.8 cm (1.5 in.). The open area of such a slot is greater than the area of a 1.27 cm (0.5 in.) diameter hole. Increasing the size of the drain slots further was considered to be impractical. Further, visual observations (in the plexiglass housing) suggest that enlargement of drain holes (even if it were practical to do so) would not necessarily improve performance; at high influent oil concentration, the oil can partially block the plates by bridging across the separating distance of the plates. This would tend to deteriorate performance of the corrugated stack configuration even further.

(4) Similar results were obtained for the right angled corrugation (Fig. 1(*b*)) stack at 1.27 cm (0.5 in.) separation distance, suggesting that increased plate separation will not necessarily alleviate the oil blocking and "foaming" problems.

(5) Reduction in the length of the corrugation (test nos. 8 and 10), however, results in significantly better performance, approaching that of the empty secondary chamber configuration. These tests suggest that large clearances between the ends of plates and any other surface are required. The large clearances prevent oil bridging and also provide some distance needed for the slow settling of the "foamy" oil-water structures. However, it is doubtful that the provision of this larger clearance will result in enhanced separation over baffled or empty horizontal configurations of *equivalent* size, mainly due to "foam" formation. At any rate, in the present configuration, even the short corrugated stack configuration, with large end clearances does not result in any enhanced settling.

Similar results were obtained for the various separator configurations when tested with a 50–50 mix of #2 and #6 fuel oils. However, in these tests #6 oil, used in previous tests, was utilized. Some of this #6 oil had high amounts of suspended or dispersed water (determined by Karl Fischer titration), which does not readily settle out. In one case 50% water in the mix was reported. It should be stated that this problem did not exist for the tests run with straight #2 and #6 oils. As explained previously, this dispersed water in the oil could increase the viscosity of the 50–50 mix considerably more than the expected 70–80 cp. Since the consistency of the mixture is questionable, the data is not reported here. It is important to note, however, that the presence of dispersed water, in this oil phase, drops the corrugated stack configuration performance significantly.

A few tests at 25% influent concentration of #2 fuel oil were run with the various secondary chamber configurations. In all cases, the performance improved. This result should be expected since at higher concentrations the average drop size is larger.

Conclusions

The following conclusions can be made as a result of this laboratory study of the design and performance aspects of horizontal flow corrugated plate separators:

(1) The mechanisms of oil separation in corrugated plates are similar to those of ordinary parallel plates; gravitational and flow fields control the capture or approach of oil drops to the top plates, while coalescence should be important for attachment when the plates are fully coated with oil.

(2) Interdrop coalescence in the flow field, due to the periodic constrictions and expansions in realistic corrugated plate stacks (i.e. gradient coagulation) is not an important mechanism of oil separation in such devices.

(3) The radius of curvature of the corrugations is not an important factor in the capture of oil drops on plates without significant oil build-up. However, this parameter may be important in terms of oil holding capacity or plate performance under conditions such that there is some oil accumulation.

(4) Vessels with corrugated plate stacks have enhanced separation characteristics over horizontal cylindrical vessels with or without baffles, under light or low viscosity influent oil conditions. With viscous (~2000 cp) oils the simpler baffled configurations work better than the corrugated plate stack configuration of equal overall dimensions.

(5) Poor performance under viscous influent oil conditions is probably due to oil blockage of the plates and low interfacial tension, eventually resulting in the formation of "foamy" oil-water constituent, dispersions. This "foam" does not readily settle due to its high specific gravity. Such phenomena should also be expected in other plate separator configurations when heavy viscous and low interfacial tension (with water) oils are present in the influent.

(6) The above phenomena can also be expected with medium viscosity oils containing high amounts of dispersed water that does not readily separate from the oil. The dispersed water can increase the effective viscosity and specific gravity of the "oil" significantly.

(7) In shipboard and other applications, where influent oil characteristics may vary and where the probability of having viscous oils and surfactants in waste water is high, simpler baffled horizontal flow vessels may have some advantages over plate separators. More field data on these devices under various oil conditions is needed.

Acknowledgment

The authors wish to thank Nelson Industries, Inc., for granting permission for publication of this paper. Certain features of this work

may be the subject of future patent applications and all patent rights are reserved.

References

1 University of Mississippi Law Center, "Oil Pollution Control Mechanisms, Statutes and Regulations", MASGP-78-014, April 1978, Mississippi-Alabama Sea Grant Consortium.

2 Osamor, F. A., and Ahlert, R. C., "Oil/Water Separation: State-of-the-Art," EPA-600/2-78-069, April 1978, Environmental Protection Agency.

3 Russel, E. C., "Fram Corporation Model OWS-23-FCI-USCG Oil/Water Separator," 2059, May 1973, U.S. Army Mobility Equipment Research and Development Center.

4 Norton, L. B., and Perrini, F., "Test and Evaluation of Oil Pollution Abatement and Devices for Shipboard Use Phase I," AD-762-498, March 1972, U.S. Coast Guard.

5 Merryman, J. G. and Osterstock, E. R., "Coalescing Plates and Packs for Oil/Water Separation in Various Shipboard Applications," 724305.2/6, 1973, U.S. Coast Guard.

6 Donahue, D., "Separating Oil from Feed Water," U.S. Patent No. 386,114, July 17, 1888.

7 Coe, H. S., "Liquid Separator", U.S. Patent No. 1,709,971, April 23, 1929.

8 Mittleman, J., "OPC-3000 Coalescing Plate Oil/Water Separator Evaluation", NCSL TM-212-77, November 1977, Naval Coastal Systems Laboratory.

9 Morrison, J., "Tilted Plate Separators for Refinery Waste Water," *Oil and Gas Journal*, Vol. 68, No. 50, December 1970, pp. 86–88.

10 Einstein, A., *Ann. Phys.*, Vol. 19, 289, 1906.

11 Abernathy, M. W., "Design Horizontal Gravity Settlers," *Hydrocarbon Process*, Vol. 56, No. 9, September 1977, pp. 199–202. L 665.05 P4972

12 API, *Manual on Disposal of Refinery Wastes: Volume on Liquid Wastes*, 1st ed., American Petroleum Institute, Div. of Refining, API, New York, 1969.

13 Sherony, D. F. and Kintner, R. C., "Coalescence of an Emulsion in a Fibrous Bed, Part I Theory", *Canadian Journal of Chemical Engineering*, Vol. 49, June 1971, pp. 314–325.

14 Schlichting, H., *Boundary Layer Theory*, 6th ed., McGraw-Hill, New York, pp. 176–178.

15 Dean, W. R., "Fluid Motion in a Curved Channel", *Proceedings of the Royal Society (London)* A121, 1928, pp. 402–420.

16 Patankar, S. V., Pratap, V. S. and Spalding, D. B., "Prediction of Laminar Flow and Heat Transfer in Helically Coiled Pipes", *Journal of Fluid Mechanics*, Vol. 62, Part 3, March 1974, pp. 539–551.

EPA 312 353 2000
800 621 8431

FAX 513 891 6685

EPA # TITLE